Building a virtual model of a baleen whale: Phase 2

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Award Number: N00014-12-1-0516

LONG-TERM GOALS

This project proposes to CT scan an entire baleen whale. The scan data will be used in a future effort (Phase 3) to build a vibroacoustic model, allowing us to simulate the interactions between the whale's anatomy sound stimuli.

OBJECTIVES

The entire project has been subdivided into three phases, each proposed and funded separately. Phase 1, where we conceived and planned the overarching strategy, has been completed. This report covers recent accomplishments for Phase 2. The plan for Phase 2 was to capture a postmortem California gray whale in an insulated towing bag, cool it with recirculating refrigerated sea water, tow it to a haul-out facility, place it in a custom fiberglass tube, and then transport the entire package to a commercial freezer. The frozen specimen would eventually be encased in a specially designed sarcophagus and transported to an industrial CT scanner. After scanning, the package containing the whale was transported to the Smithsonian Institution where it is systematically taken apart so that the elastic properties of the tissues could be measured. The CT scan data and tissue property measurements could be combined in a future effort to construct a finite element model, separately planned and funded in Phase 3.

APPROACH

Oceanic sound levels have increased steadily over the last half-century (McCarthy, 2005), especially the low-frequencies, due to geologic exploration, industrial development, shipping, and military activities. Low frequency sounds have been known to negatively impact large whales (Frantzis, 1998; Balcomb and Claridge, 2001; Malakoff, 2002) and potentially other living marine organisms.

Navy sonar training operations have been hampered by concerns and lawsuits over the effects that high intensity sound exposure might have on marine organisms, specifically the mammals. Since the Navy is responsible for knowing any impact that its operations might have on living marine resources, it is important to work toward a methodology that will provide a test-bed to facilitate and promote the assessment of vibroacoustic impacts.

There is worldwide interest in the potential effects of anthropogenic sound on mysticete (baleen) whales. Most of the research on the effects of sound has been conducted on a few small marine mammal species that can be housed in research labs and aquaria but relatively little is known about all large marine mammals, mysticetes foremost among them. Long wavelength, low-frequency sounds are likely to have their most significant interactions with the bodies of large animals. The large body size of mysticete whales precludes any meaningful bioacoustic work in captivity. Consequently, our assessment is that the most effective way to study the vibroacoustic physiology of these animals is to construct a model of mysticete anatomy that can be used to study the interactions between the whales and low-frequency sounds. Improvements in industrial x-ray computed tomography (CT) scanners have made it feasible to scan an adult mysticete.

Vibroacoustic computer models based on the principles of finite element (FE) analysis have several advantages. They can applied to a wide variety of species and acoustic stimuli. Once developed, models are inexpensive to reuse in light of new information or new questions. The models we have built are primarily constructed at the organismal level. This allows us to investigate a variety of interactions, from those that impact the whole organism, to those that address questions of sound propagation and transmission across interfaces between suites of structures. We can also investigate the distribution of acoustic pressures and shear stresses, dissipated energy and heating effects, excessive strains or displacements due to resonance, the potential to induce cavitation, and most importantly, exploit the ability to produce reasonable approximations of hearing sensitivity by constructing *predictions of audiograms*.

Our team has pioneered a suite of techniques that combine the anatomic geometry obtained from CT scans (Cranford, 1988; Cranford *et al.*, 1996; Cranford *et al.*, 2014; Cranford and Krysl, 2015) with measurements of tissue elasticity (Soldevilla *et al.*, 2005; Hess *et al.*, 2006; Oberrecht, 2014) and our custom finite element analysis software (Krysl *et al.*, 2006), the *vibroacoustic toolkit* (VTk). This combination of techniques produces a versatile computational environment for vibroacoustic simulations (Krysl *et al.*, 2008). Our suite of techniques can also be applied across a broad taxonomic spectrum to assess acoustic exposure.

The value of these methods has been demonstrated and validated. For example, our publications have revealed previously undiscovered mechanisms and pathways for sound reception in toothed whales (Cranford *et al.*, 2008a) and baleen whales (Cranford and Krysl, 2015). These results have challenged some of the primary historical assumptions about sound reception in these organisms (Norris, 1968; Tubelli *et al.*, 2012). In addition, anatomic similarities and differences among living toothed and baleen whales suggest scenarios for how these new sound reception pathways may have evolved from the original pathways used by the ancient whales (archaeocetes) in the Eocene.

These computer-enabled investigative methods have already transformed our capacity to generate original knowledge and to better understand the bioacoustics of marine mammals (Cranford, 2000; Cranford and Amundin, 2004; Cranford *et al.*, 2008a; Cranford *et al.*, 2008b; Cranford *et al.*, 2014; Lancaster *et al.*, 2014; Cranford and Krysl, 2015). The resulting simulations allow us to emulate, for example, the biosonar signal generation mechanism and the formation of an acoustic transmission beam, or to measure the amplitude differences and time delays for sounds reaching each of the ear complexes, or produce synthetic audiograms for species that are otherwise inaccessible for study. These are just a few examples of the predictions and understanding we can glean from basic vibroacoustic simulations, *all of these mechanisms can be teased apart using quantifiable biomechanical interactions within the organism*.

We can now apply these powerful tools to (1) investigate the details of sound reception mechanisms in the baleen whales and (2) test mitigation strategies for any potential problems that may be uncovered.

WORK COMPLETED

(1) Fin whale (*Balaenoptera physalus*):

We have produced and published the first predicted audiogram for a baleen whale. Using our vibroacoustic toolkit (VTk), we constructed a finite element model of a fin whale head from CT scan data in our library. Our simulation results about vibroacoustic modeling of a small fin whale head was published in PLoS ONE in January 2015 (Cranford and Krysl, 2015). Our future plans include working toward understanding the directional nature of sound reception for mysticetes in Phase 3 of the overall effort to understand mysticete hearing mechanisms. We have already submitted a grant request to fund Phase 3.

(2) Common minke whale (*Balaenoptera acutorostrata*):

We were unable to acquire a postmortem gray whale specimen for this project, as originally planned. Alternatively, we acquired an entire carcass of a freshly postmortem juvenile minke whale (*Balaenoptera acutorostrata*); froze it; packaged it; shipped it to Hill Air Force Base in Utah; and conducted a high resolution CT scan (the first such scan of an entire baleen whale using an industrial CT scanner).

This demonstrates the successful completion of the primary objective of Phase 2. Some anatomic components have now been segmented.

RESULTS

(1) Fin whale (*Balaenoptera physalus*):

Using our vibroacoustic toolkit (VATk), we constructed a finite element model of a fin whale head from CT scan data in our library. Our simulation results about vibroacoustic modeling of a small fin whale head was published in PLoS ONE (Cranford and Krysl, 2015).

That paper predicted the first hearing sensitivity curves for any baleen whale, including convincing evidence that there are probably two sound reception mechanisms in the fin whale (and perhaps all mysticete whales). The most intriguing result (Figure 1) is that the greatest sensitivity to low-frequency sound reception in the fin whale is due to a *bone conduction mechanism*. This mechanism is activated when long wavelength sounds interact with the whale's emormous skull bones, causing patterns of deformation that propagate through various cranial bones to the bony ear complexes. These "synthetic" audiograms predict frequency sensitivity for both types of sound reception mechanisms (pressure through soft-tissue and bone conduction). Frequency sensitivity curves provide valuable new insight and information for Navy monitoring efforts because they span the range of acoustic frequencies that are pertinent for mysticetes and a preponderance of oceanic anthropogenic noise spectra (National Research Council, 2003; Cranford and Krysl, 2015).

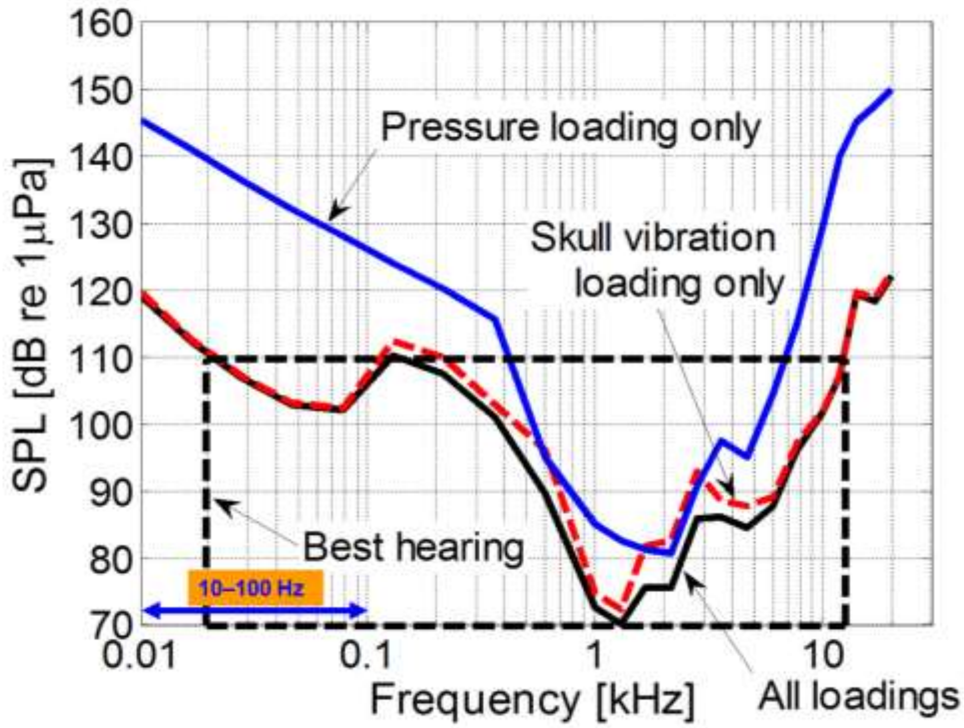

Figure 1 - Predicted audiogram for a fin whale. The red dashed line shows the sensitivity curve given by bone conduction mechanism, as calculated by the FE models of the entire head. This "bone conduction curve" yields the greatest sensitivity across most of the frequency range (from 10 Hz – 10 kHz) when compared to the solid blue curve. The solid blue curve represents frequency sensitivity for pressure loading on the tympanic bulla through a soft-tissue pathways. Note that the largest difference (>20 dB) between the red and blue curves, occurs within the frequency range between 10-100 Hz, the same frequency range in which fin whales produce their songs or vocalizations. The solid black curve represents frequency sensitivity when all loadings are considered. The minimum threshold or "minimum audible pressure" is taken from the literature on odontocete hearing (since we do not have such a value for mysticetes). The reasoning behind this can be found in the Supplementary Information section of the paper on the PLoS website (www.plosone.org/article/info:doi/10.1371/journal.pone.0116222).

We also investigated whether the size of the bony ear complex in a young fin whale could bias the simulation results. By measuring a diverse sample of cetacean skulls and tympanoperiotic complexes, we have shown that very young whales have adult size ears. This precocial development of the tympanic bulla of the bony ear complex is widespread among cetaceans and probably common to all of them, as reported in one of our publications (Lancaster *et al.*, 2015).

We have also validated our modeling methodology by comparing results from simulations with published results from live animal biosonar research (Cranford and Krysl, 2013). Collectively, our research results butress the notion that the cetacean head works like an *acoustic antenna* (Norris, 1968; Norris, 1975; Norris, 1980; Cranford *et al.*, 2015; Ary *et al.*, 2016; Krysl and Cranford, 2016), essentially gathering inputs from many points over the skin and processing them according to frequency, amplitude, and input location.

It is logical that the ability to receive low frequency sounds in mysticetes must also be coupled with a capacity to sense the direction of the source of these signals, otherwise the ability to sense them would have little consequence. We conducted a preliminary simulation to determine if the input to the TPCs is different when the direction of the sound stimuli changes. Here we report the first preliminary result of this test (Figure 2). Since the greatest sensitivity (lowest threshold) occurs at just over 1 kHz, we projected a 1 kHz signal at the modelled head from two different directions (0° and 45°), and noted the patterns of deformation that reach the tympanic bullae. In simple terms, the deformation patterns are similar at both TPCs when the stimulus arrives from directly in front of the animal but asymmetric when the sound stimulus arrives from 45°. This preliminary result indicates that these animals do have the ability to discern source direction for at least some low frequency acoustic sources. This sensory ability may be related to the phase of the arriving sound waves.

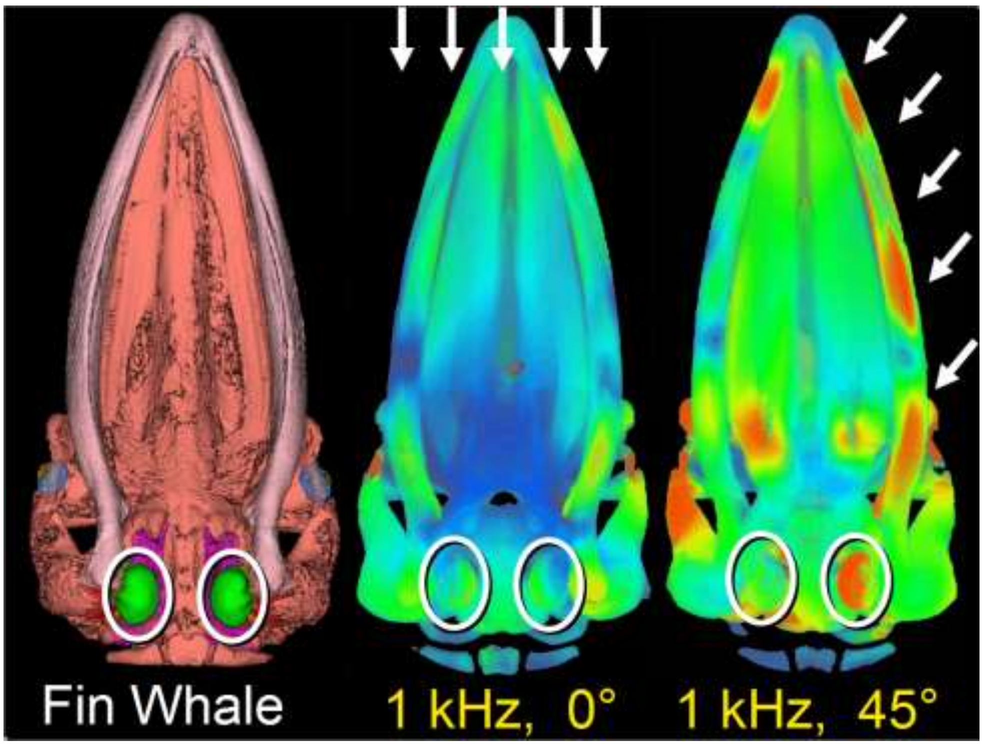

Figure 2 - Ventral views of the fin whale skull; (A) anatomic context, showing tympanic bullae in green; (B) deformation diagram of displacement amplitude when 1 kHz sound arrives from directly in front (0°) of the whale. Note that the displacement pattern (as indicated by the color map) is more or less symmetrical for both bullae; (C) deformation diagram of displacement amplitude when 1 kHz sound arrives from 45° to the right side. Note that the patterns of deformation (color map) across both bullae are asymmetrical when the sound arrives from 45°. This suggests that phase may provide cues to the direction of the source. <u>These results are only preliminary!</u>

Our work clearly demonstrates that the mysticete skull plays a significant role in low frequency sound reception, confirming speculation that is more than 100 years old (Lillie, 1910). This leads quickly to questions about the potential influence of skull geometry. Since skull vibration appears to be an important component in mysticete sound reception and hearing, we must ask, what are the effects of mysticete skull geometry on their audiograms? Skull geometry in mysticetes is diverse, as shown by the examples in Figure 3 (3a, 3b, and 3c), and is probably shaped by multiple selective pressures, like feeding mode or prey type, locomotor patterns, habitat type, and perhaps auditory sensitivity. Future

work will investigate the effects of skull geometry on the bone conduction mechanism and resulting audiograms.

Figure 3a - Cosmopolitan, lunge feeding Balaenopteridae

Figure 3b - Coastal, benthic feeding Eschrichtiidae

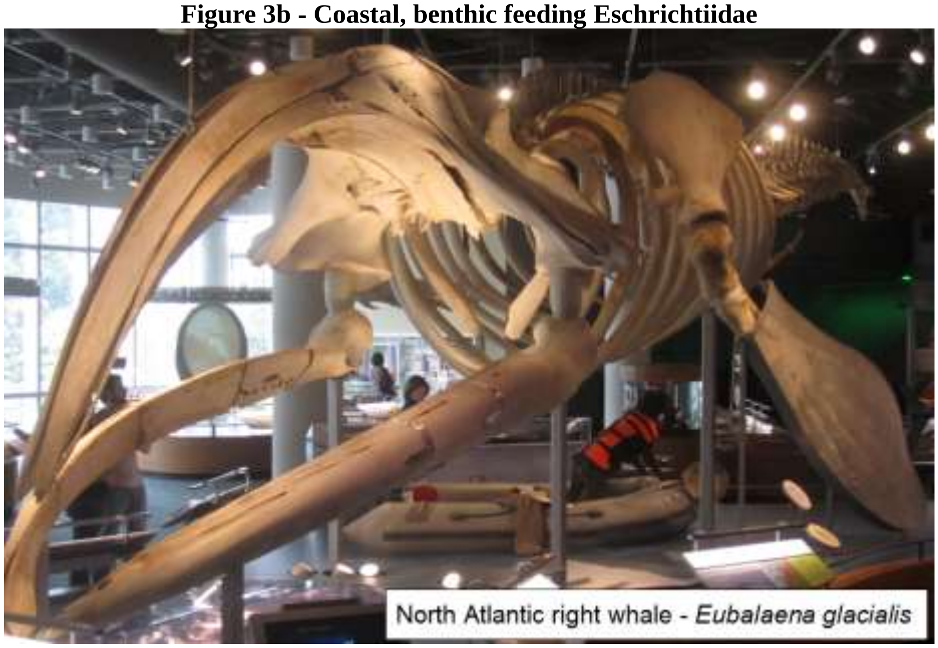

Figure 3c - Coastal and continental shelf, skim feeding Balaenopteridae

The questions of directional hearing and the effects of skull geometry on sound reception will be addressed in future studies.

(2) Common minke whale (*Balaenoptera acutorostrata*):
We obtained a minke whale that stranded alive on the Maryland coast. The State Veterinarian determined that the animal had to be euthanized. Within a few hours, colleagues from the Smithsonian Institution collected the specimen and delivered it to their freezer facility in Suitland, MD.

In January 2015 we conducted a high resolution CT scan of the minke whale specimen at Hill AFB in Utah. In the intervening months we reconstructed the minke whale from CT data into a 3D volumetric representation (Figure 4).

Figure 4 - Volumetric representation of the minke whale reconstructed from CT scans.

We have also dissected the specimen at the Smithsonian Institution in collaboration with a group of experts from around the world.

Figure 5 - Experts dissect minke whale specimen at the Smithsonian Institution.

It should be noted that reconstructing an entire baleen whale, even a small one, from a series of high-resolution CT scans is a significant challenge. When the complete series of CT scans is reconstructed at the highest resolution, the single volume is larger than 24 Gb, requiring powerful computers to display or manipulate the entire volume in real time. Throughout the entire body of the whale, each individual scan section contains pixels that are 0.6 mm on a side. This is exquisite anatomic resolution for an animal of this size.

As a consequence of the immense size of the dataset and anatomic geometry, a great deal of work remains.

The process of meshing the anatomic components to build a vibroacoustic model will be accomplished in Phase 3, a future project.

IMPACT/APPLICATIONS

Transitions and implications

The success of this project marks a sudden and conspicuous transformation in our understanding of the anatomy and sound reception mechanisms in mysticetes. The methodology developed for this project significantly advances our understanding of the functional morphology of cetacean bioacoustics.

There is one major advancement that accrues from capturing in situ anatomy in an entire mysticete whale. As we have learned from our work with the toothed whales, quantifying the anatomic geometry of various organs and tissue interfaces is essential for understanding overall acoustic function, free of bias by preconceived expectations. In addition, the sizes, shapes and material composition of these organs and tissue interfaces will determine their interaction with acoustic stimuli. The suite of techniques we developed to CT scan an entire whale carcass is unique and foundational because it provides sufficient resolution in anatomic geometry to allow vibroacoustic simulations.

The long-term, overarching research effort put forth here is robust and can also test mitigation strategies and inform regulatory decision makers about expectations of the effects, or lack thereof, from the sounds that large marine mammals and fish are exposed to from anthropogenic sources.

RELATED PROJECTS

Our current project, to CT scan an entire baleen whale and build a vibroacoustic model of it, is an outgrowth of an effort that was originally supported as a pilot project in 2004 by Dr. Frank Stone at the Chief of Naval Operations Environmental Readiness Division. That innovative project resulted in the development of the *vibroacoustic toolkit* (VATk) and a number of published papers (Krysl *et al.*, 2006; Cranford *et al.*, 2007; McKenna *et al.*, 2007; Cranford *et al.*, 2008a; Cranford *et al.*, 2008b; Krysl *et al.*, 2008; Cranford *et al.*, 2010; McKenna *et al.*, 2011; Barroso *et al.*, 2012; Castellazzi *et al.*, 2012; Cranford and Krysl, 2012; Krysl *et al.*, 2012a; Krysl *et al.*, 2012b; Cranford *et al.*, 2014; Oberrecht *et al.*, 2014; Cranford *et al.*, 2015; Lancaster *et al.*, 2015; Ary *et al.*, 2016; Krysl and Cranford, 2016).

That initial success led directly to our ongoing project to synthesize odontocete audiograms based upon the CT scanning and the vibroacoustic modeling methodology we developed. We have passed two significant milestones: (1) validating the vibroacoustic modeling methodology by simulating sound production and beam formation in the bottlenose dolphin and matching it to previously published results with live dolphins (Cranford *et al.*, 2014), and (2) producing synthetic audiograms for a mysticete whale and identifying the mechanism that allows them to have increased sensitivity to low frequency sounds (Cranford and Krysl, 2015).

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